



The University of Texas at Austin
Department of Physics
College of Natural Sciences

Alfvénic turbulence in the solar wind

An overview

Anna Tenerani

C. González, C. Shi, N. Sioulas, O. Panasenco, L. Matteini, M. Velli

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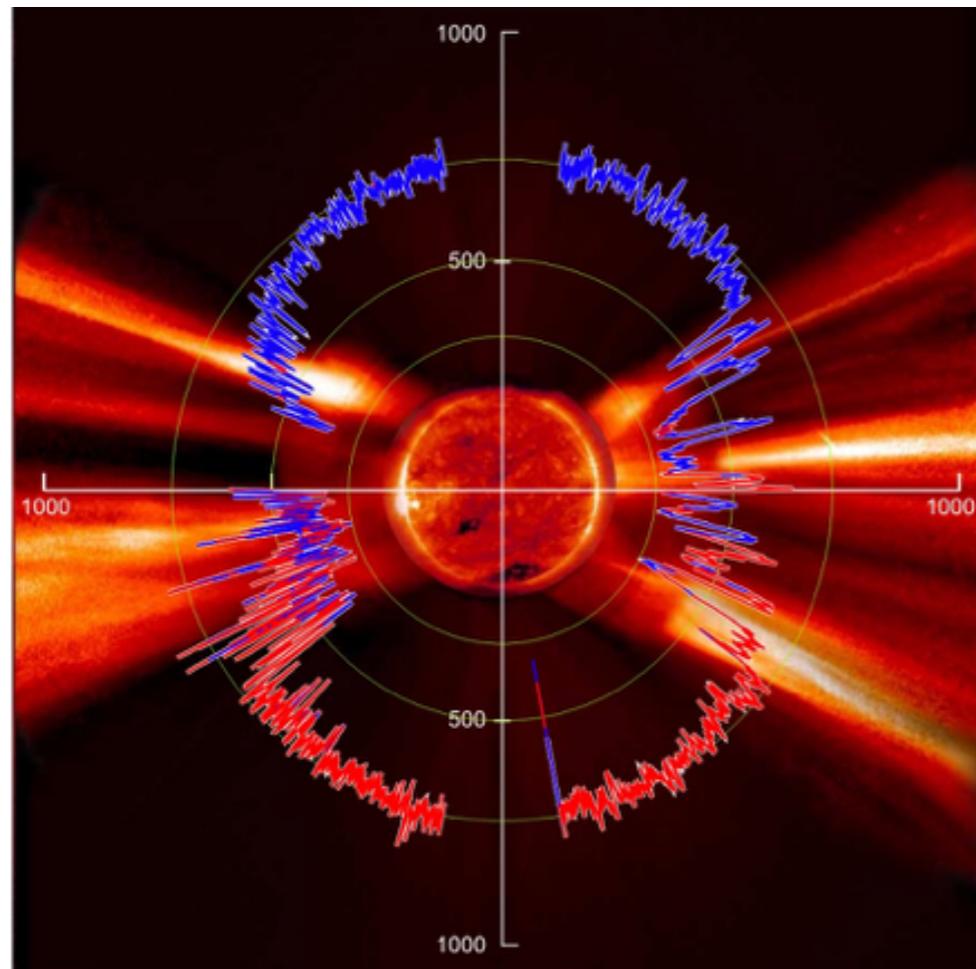
Outline

- Alfvénic fluctuations in the solar wind: an introduction
- Evolution of switchbacks: simulations and observations
- Beyond MHD: kinetic effects via extended MHD and hybrid simulations
- Conclusions

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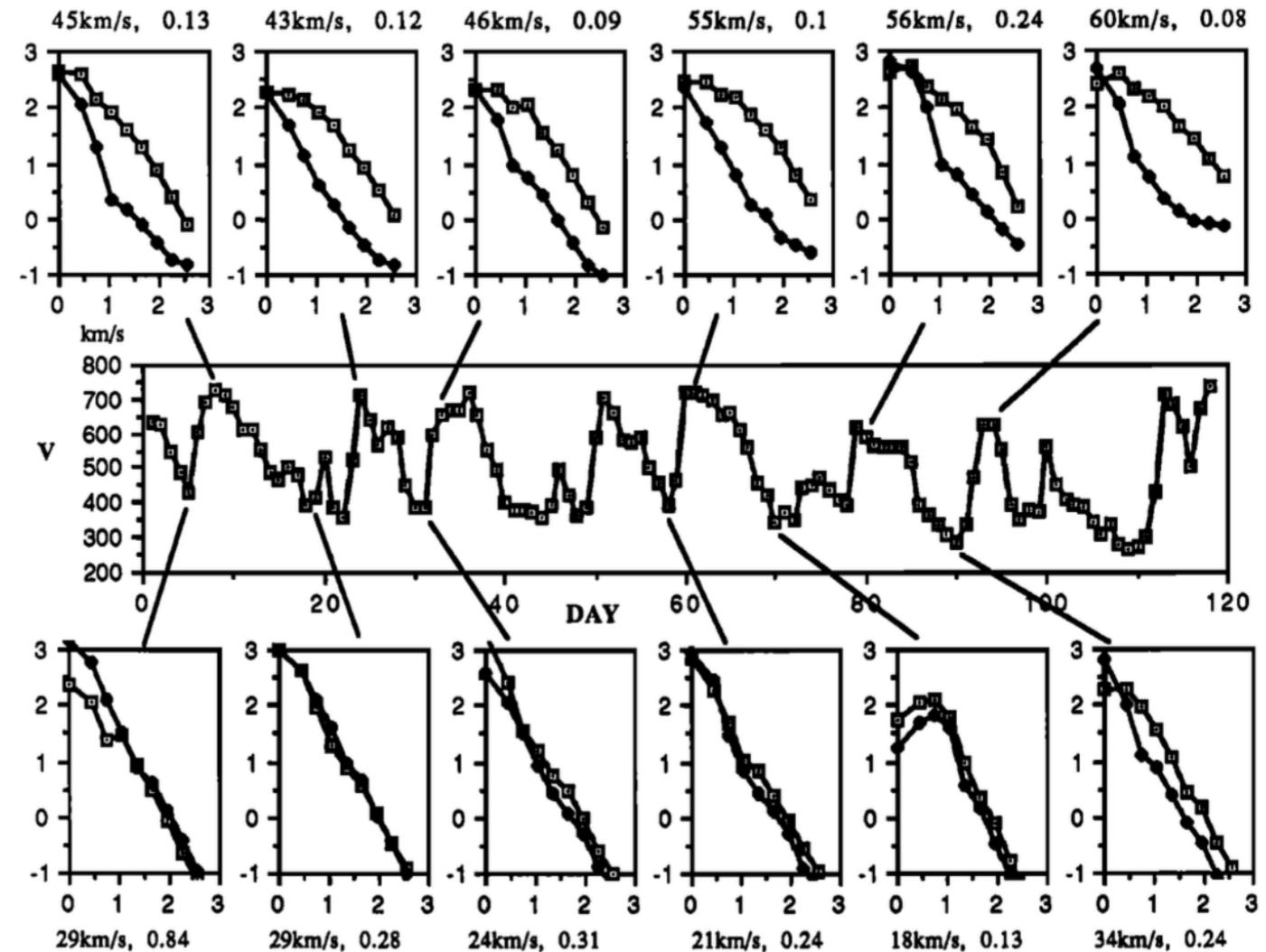
Two types of wind



Exploring the heliosphere out of the ecliptic: the Ulysses mission

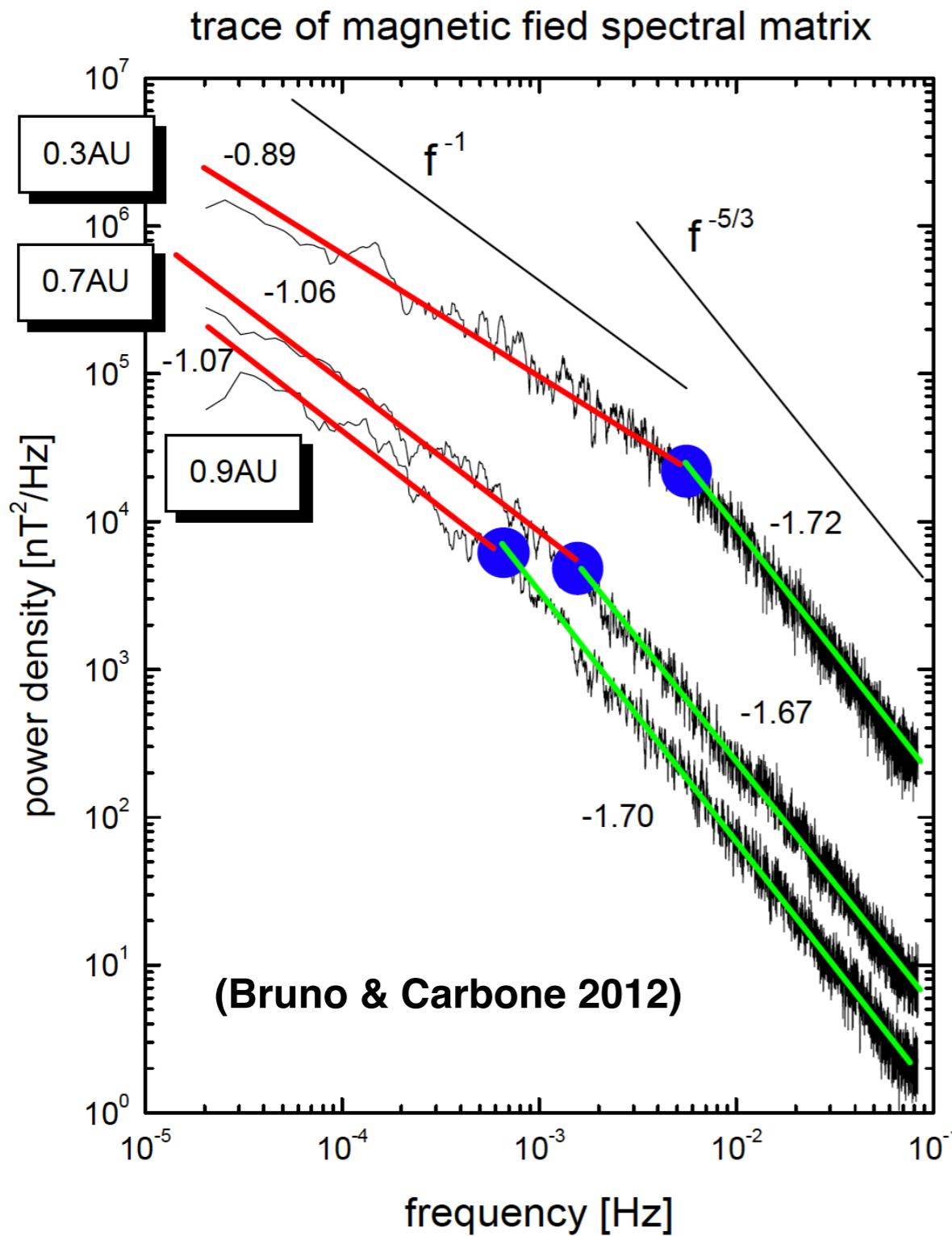
Typical configuration (at solar minimum) of magnetic field structure and slow/fast wind

Two different types of turbulence



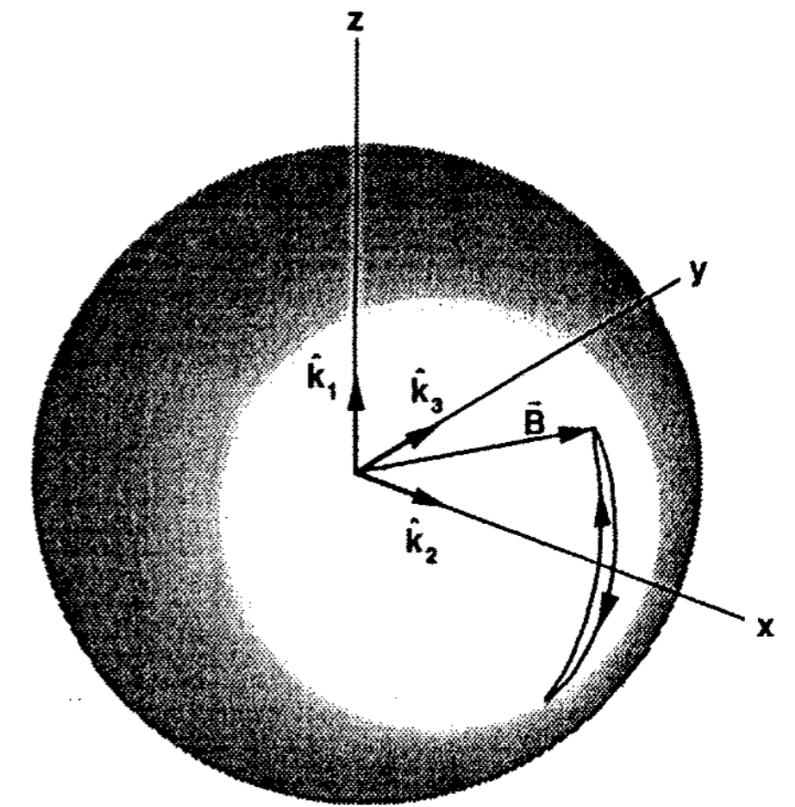
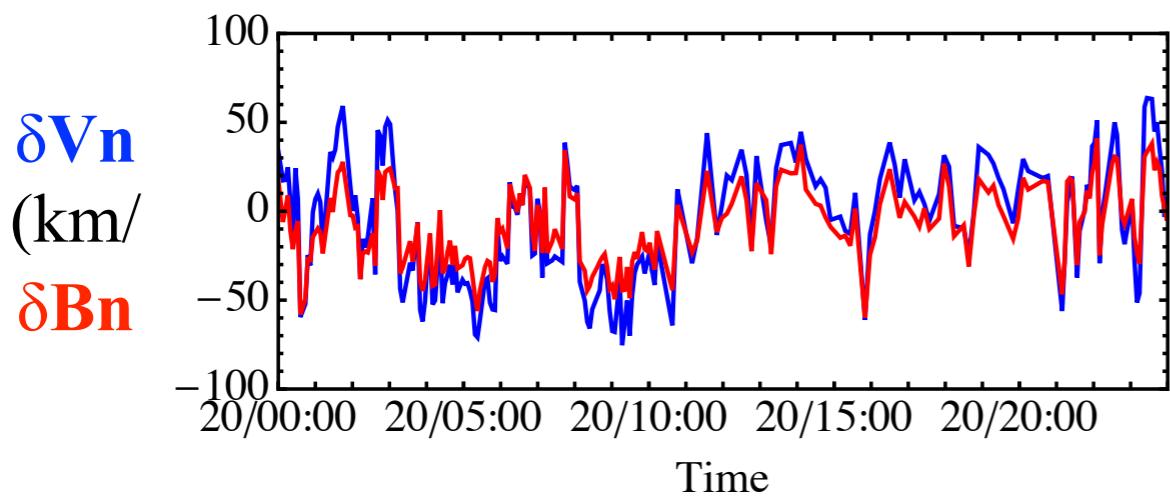
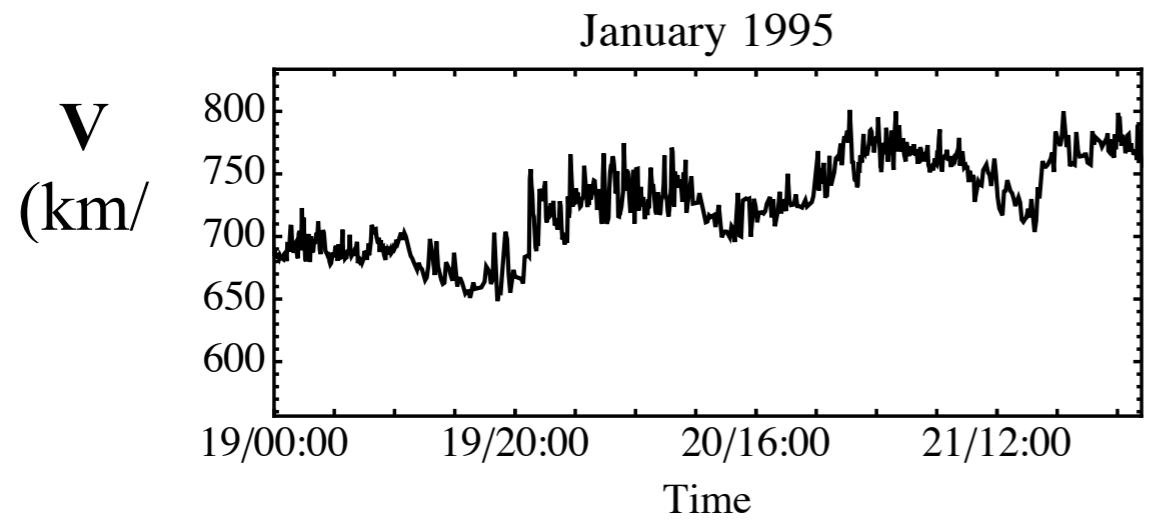
[Helios data, Grappin et al. JGR 1990]

Alfvénic turbulence from 0.3 AU to 1 AU

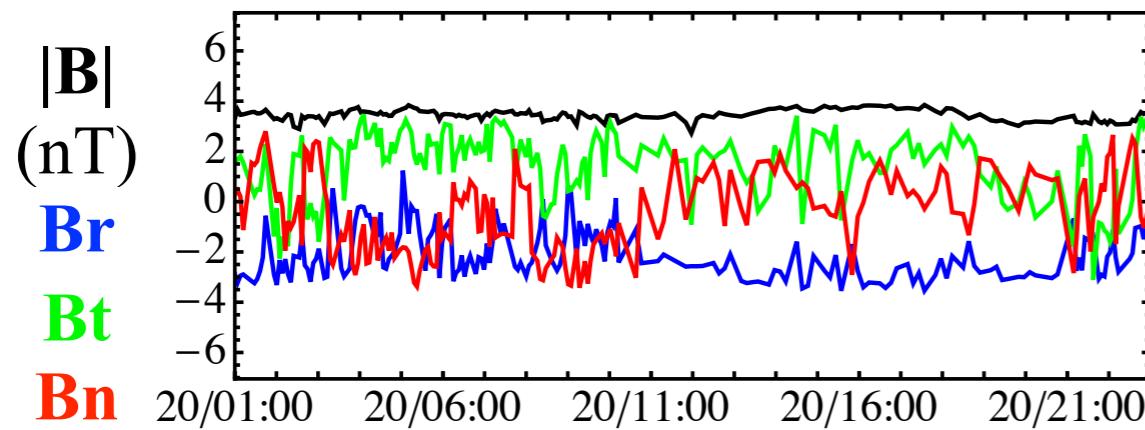


- $|\delta \mathbf{B}|/B_0 \sim 1$
- $\delta |\mathbf{B}|/B_0 \ll 1$
- $\delta \mathbf{B}/\sqrt{\rho \mu_0} \sim \pm \delta \mathbf{V}$
- mainly propagating outward
- Developed spectrum
- $\delta \rho / \rho \ll 1$

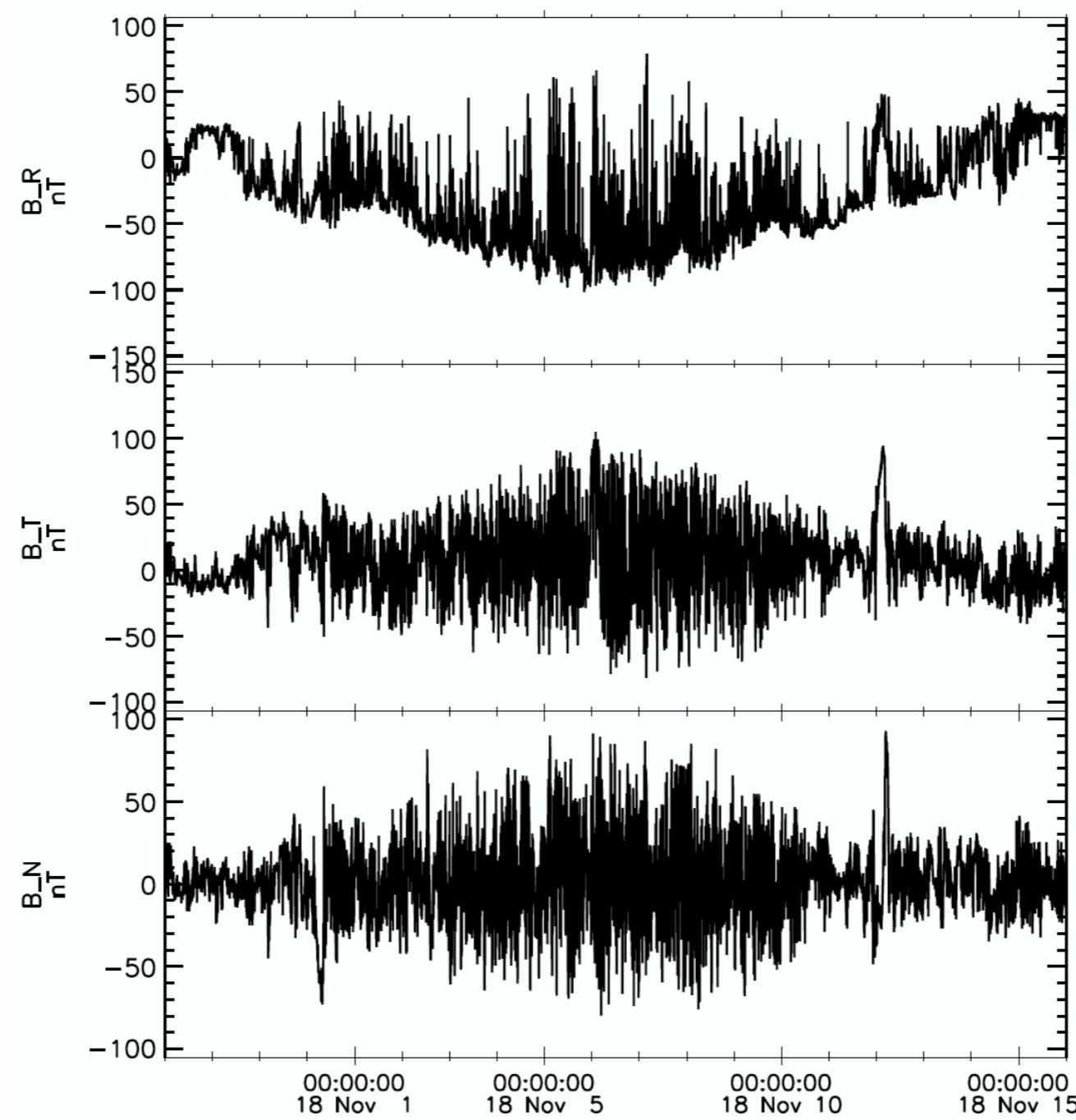
Alfvénic turbulence from 0.3 AU to 1 AU



(from B. Tsurutani et al. PPCF 1997)

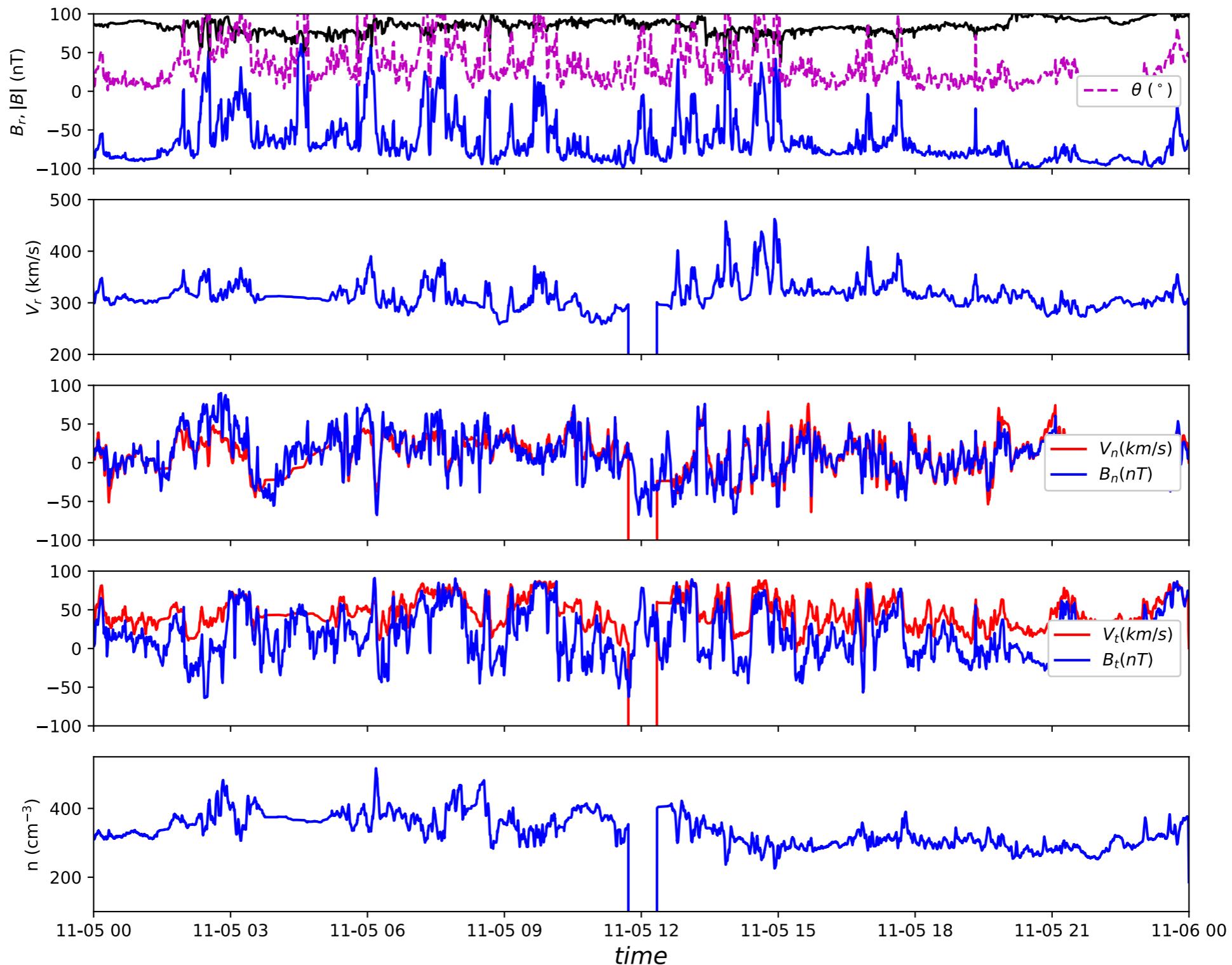


PSP first perihelion overview



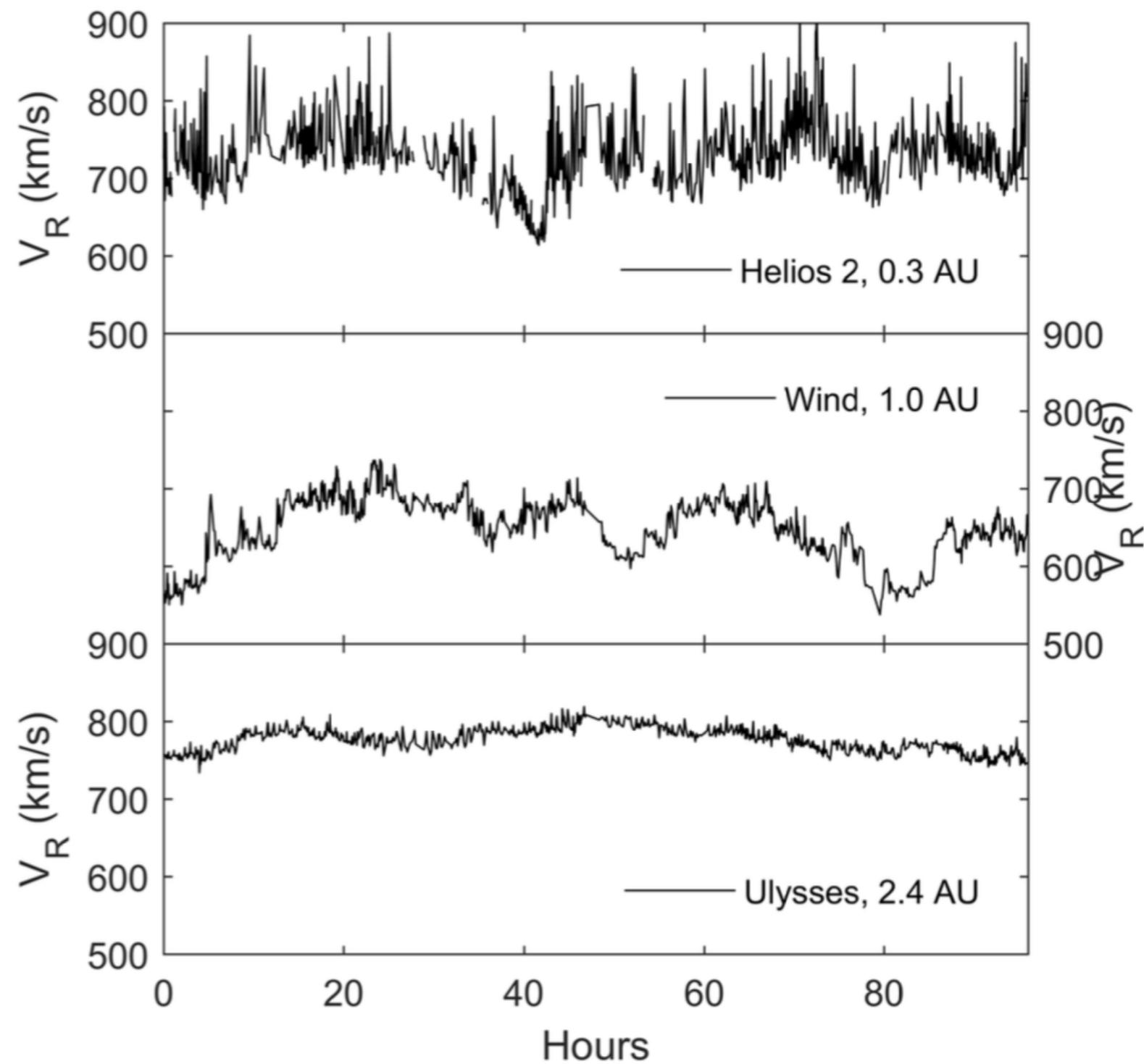
Magnetic field data from FIELDS, 1 min res (see also Bale et al. Nature 2019)

Switchbacks seen by PSP

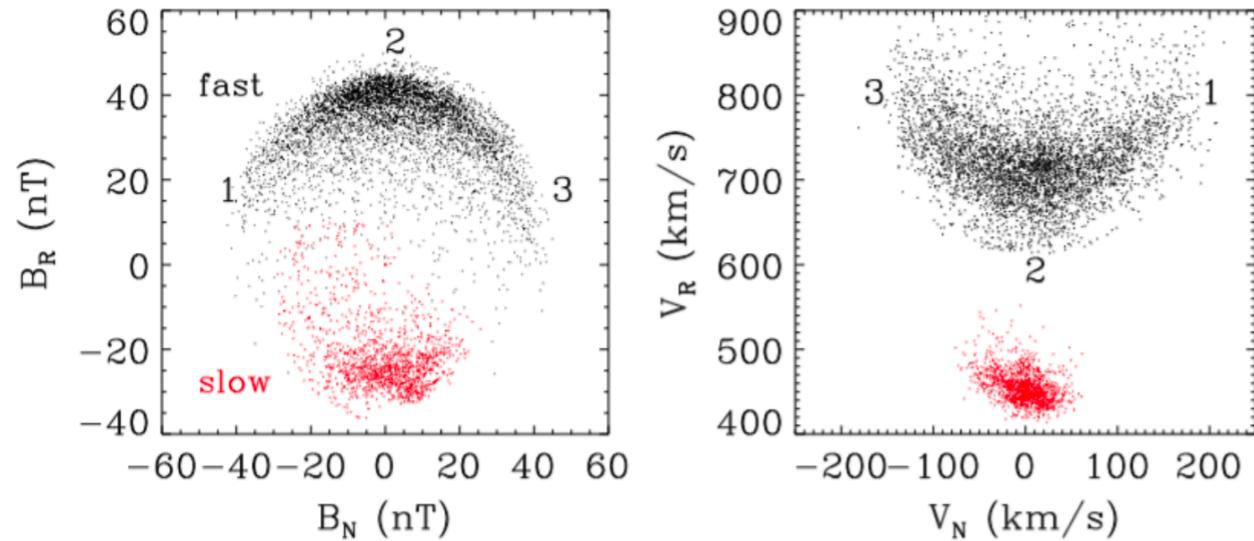


(Tenerani et al. ApJS 2020)

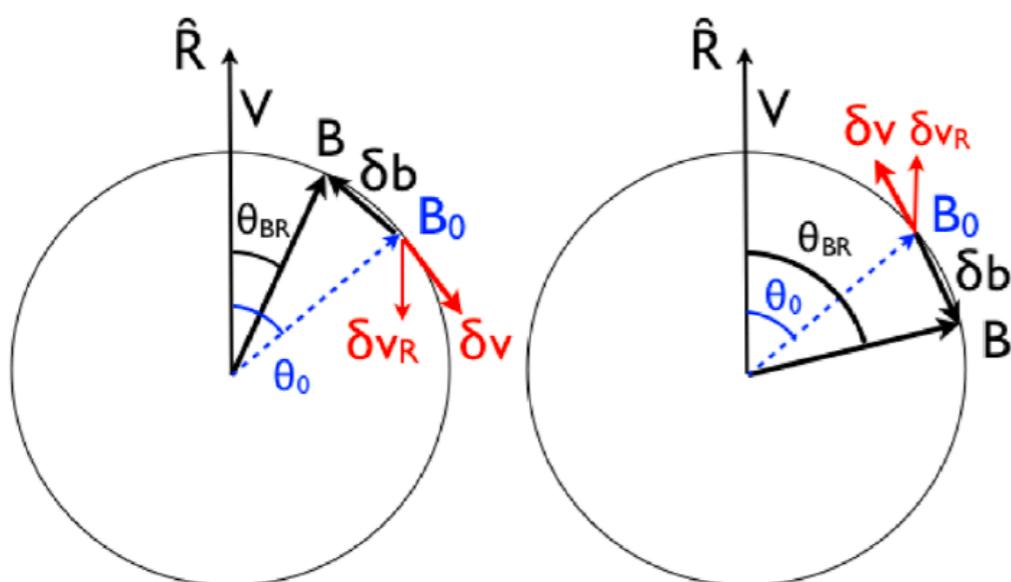
One-sided jets in solar wind radial profiles



Switchbacks and jets explained (kinematically!)



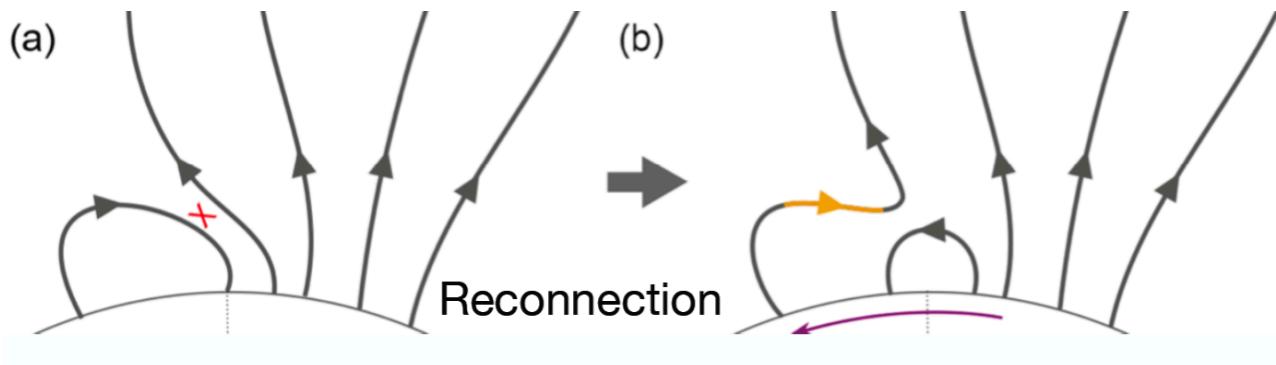
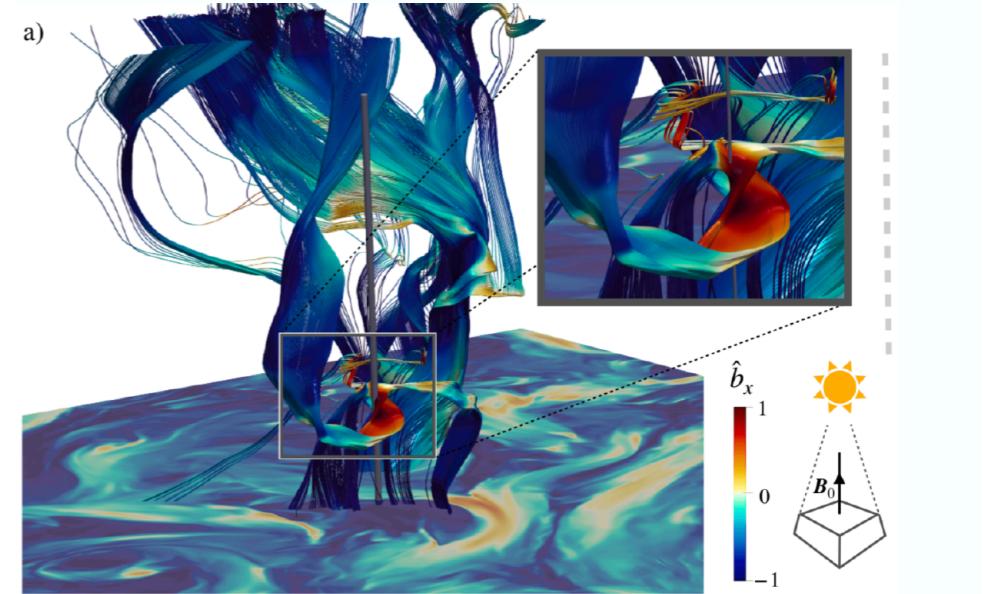
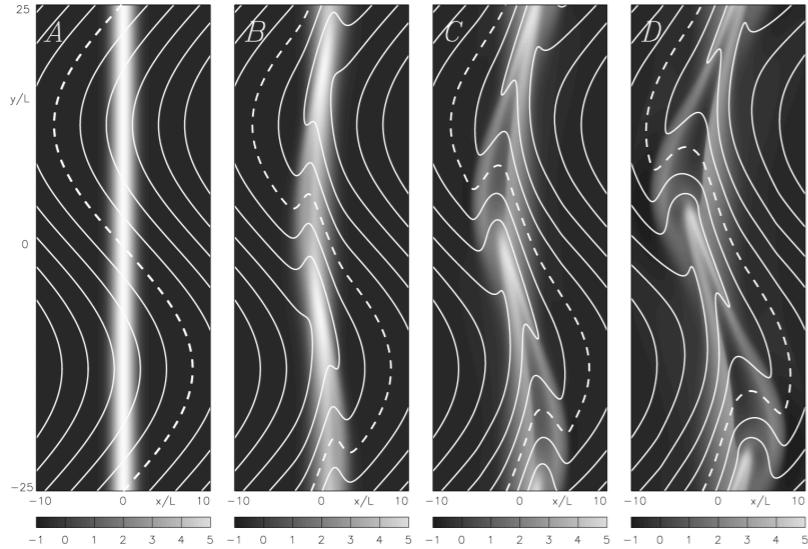
- Switchbacks are the magnetic field manifestation of radial jets (or viceversa)
- Switchbacks are a consequence of the Alfvénic character of (3D) fluctuations and $|B| = \text{constant}$



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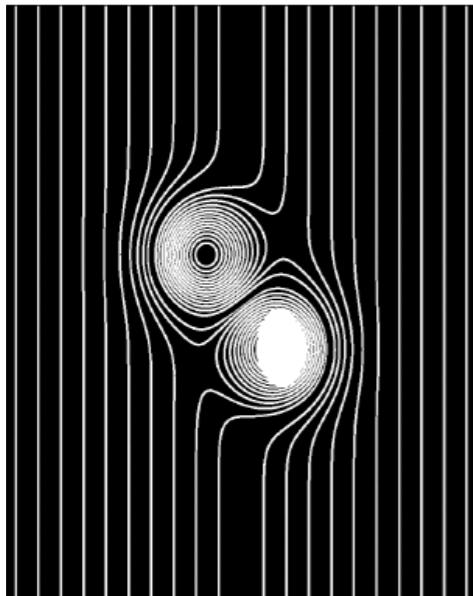
Coronal origin or in-situ? (Are they proxy for coronal processes?)



(MacNeil et al. MNRAS 2020)

A product of reconnection (Drake et al 2021, Zank et al 2021)

How do switchbacks evolve?



Understanding how such structures evolve can shed light on:

- their origin
- whether they might contribute to turbulence and plasma heating

Non-constant B Alfvénic kinks of magnetic field expand and “unfold” over a few dynamical time-scale

Alfvénic solutions to the MHD equations

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla \left(p + \frac{1}{8\pi} B^2 \right) + \frac{1}{4\pi\rho} \mathbf{B} \cdot \nabla \mathbf{B}$$

$$\frac{\partial \mathbf{B}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{B} = \mathbf{B} \cdot \nabla \mathbf{u} - \mathbf{B} (\nabla \cdot \mathbf{u})$$

$$\mathbf{z}^\pm = \mathbf{u} \pm \frac{\mathbf{b}}{\sqrt{4\pi\rho}}$$

$$\frac{\partial \mathbf{z}^\pm}{\partial t} + (\mathbf{U}_0 \mp \mathbf{V}_a) \cdot \nabla \mathbf{z}^\pm + \mathbf{z}^\mp \cancel{\cdot} \nabla \mathbf{z}^\pm = 0$$

Purely correlated or anti-correlated \mathbf{u} and \mathbf{b} fluctuations provide an exact solution (at arbitrary amplitude)

Model for switchbacks

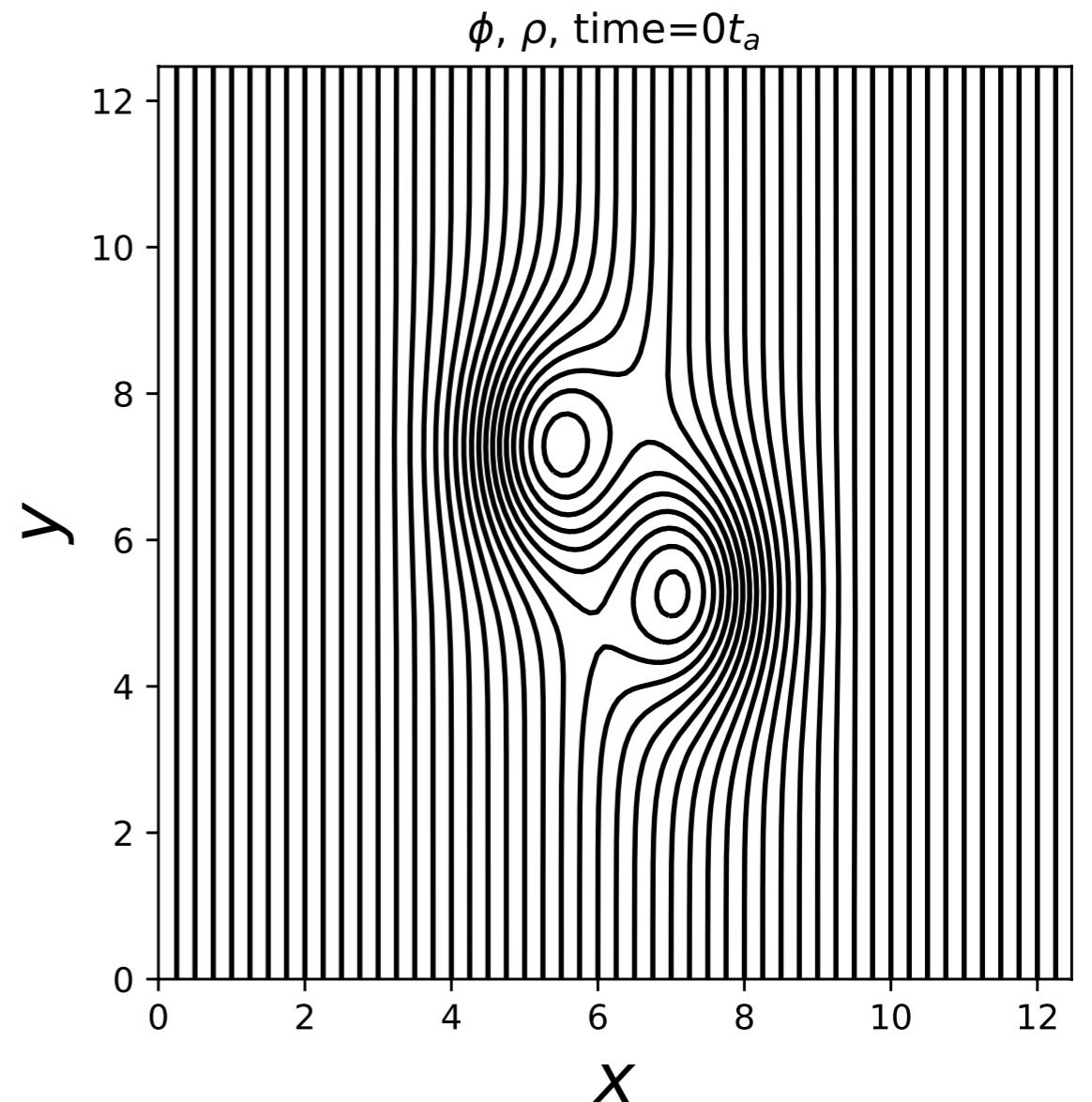
$$\mathbf{B} = B_0 \hat{\mathbf{x}} + \nabla \times \phi(x, y) \hat{\mathbf{z}} + B_z(x, y) \hat{\mathbf{z}}$$

$$\phi(x, y) = A(e^{-r_1^2} - e^{-r_2^2})$$

$$r_{1,2}^2 = \frac{(x - x_{1,2})^2}{\lambda_x^2} + \frac{(y - y_{1,2})^2}{\lambda_y^2}$$

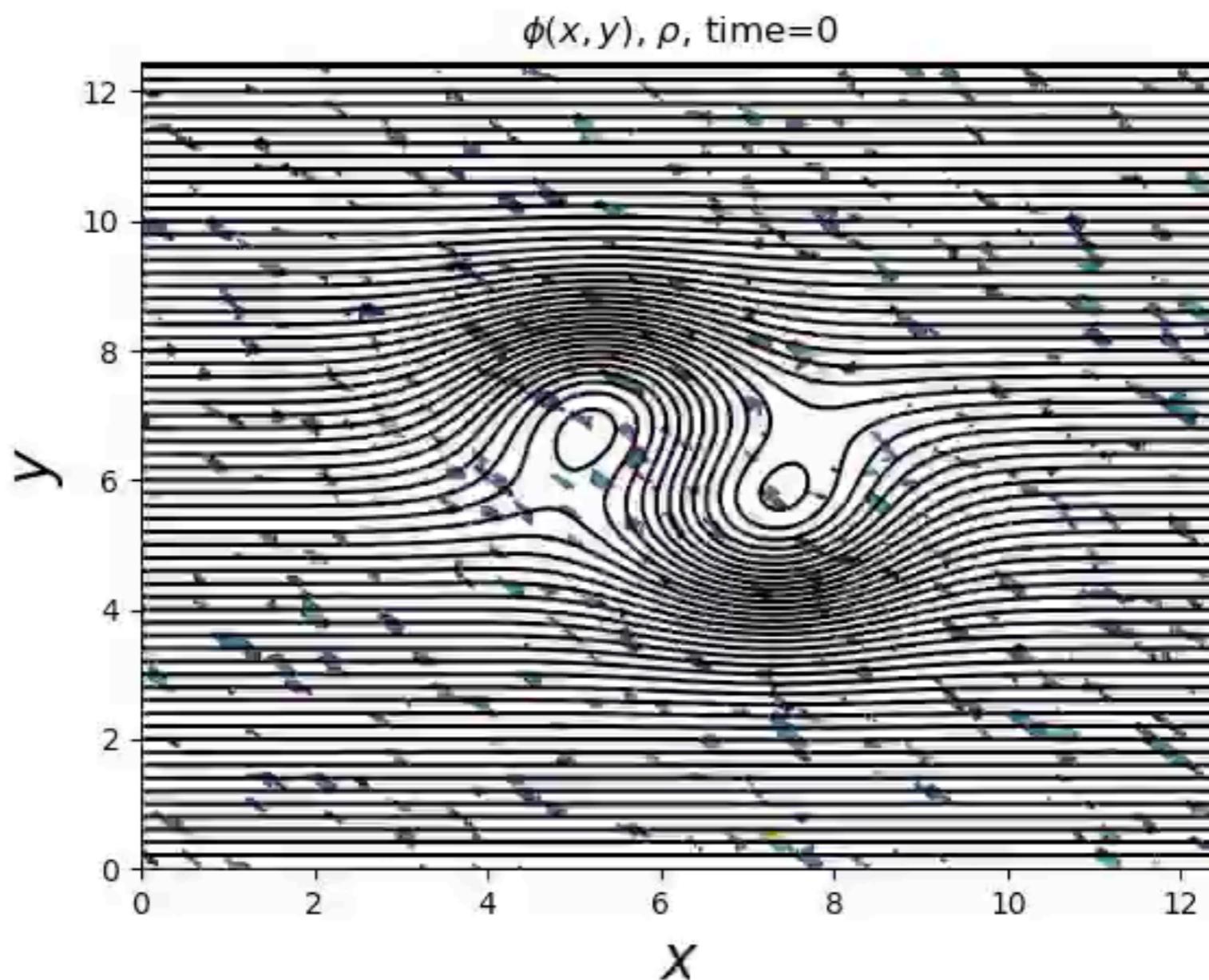
$$B_z(x, y)^2 = B^2 - (B_x(x, y)^2 + B_y(x, y)^2)$$

$$\mathbf{u} = -\mathbf{B}/\sqrt{\rho_0}$$



(Tenerani et al. ApJS 2020)

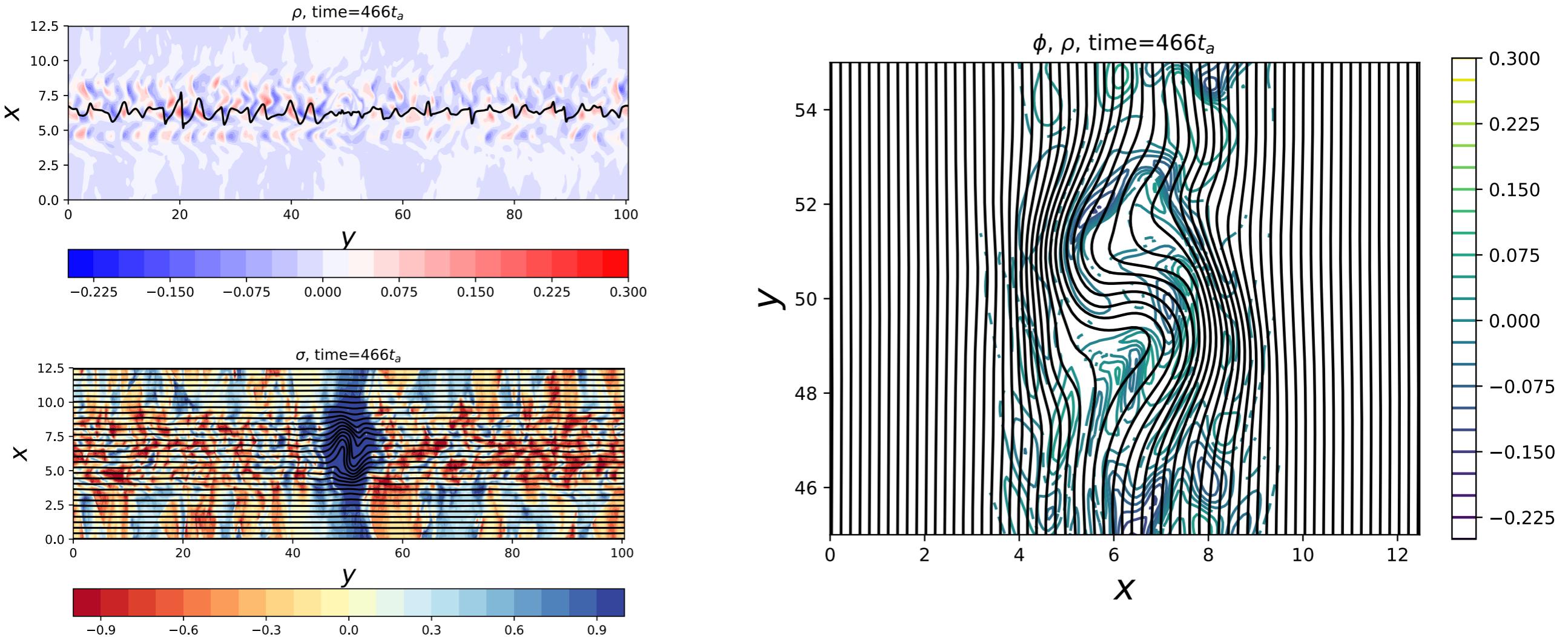
Switchback evolution



Magnetic field lines (black) and density contours (color coded)

(Frame of reference moving with the kink)

Evolution in a large scale system ($L_y/\lambda_y \sim 70$)



The effect of parametric decay becomes weaker and weaker for increasing system size. Density fluctuations and a mixture of forwards/backward fluctuations are generated **outside** the switchback, which maintains a high degree of coherence ($\sigma=1$) and persists beyond $460 t_a$

Factors affecting switchback evolution

- If the background state is homogeneous, the process that eventually leads to a breakdown of the initial state is the well known parametric decay instability, that provides an upper bound to the lifetime of switchbacks, with increasing lifetime for increasing system size.
- In our worst case scenario $T_{\text{life}} \sim 200$ Ta, yielding $\Delta R \sim 18$ Rs. A larger distance is spanned for ‘unperturbed’ path, up to $\Delta R > 43$ Rs.
- What may affect the above estimates:
 - Expansion and related large scale underlying gradients may affect the above estimates
 - Non-periodicity (random scattering rather than coherent interactions with density fluctuations)
 - Other inhomogeneities
- **Parametric instabilities are a plague that seems to be unavoidable also in the solar wind. This suggests that in the absence of some dynamical driver the occurrence of s/b should decrease with radial distance. Otherwise, their occurrence rate could be stationary or increasing.**

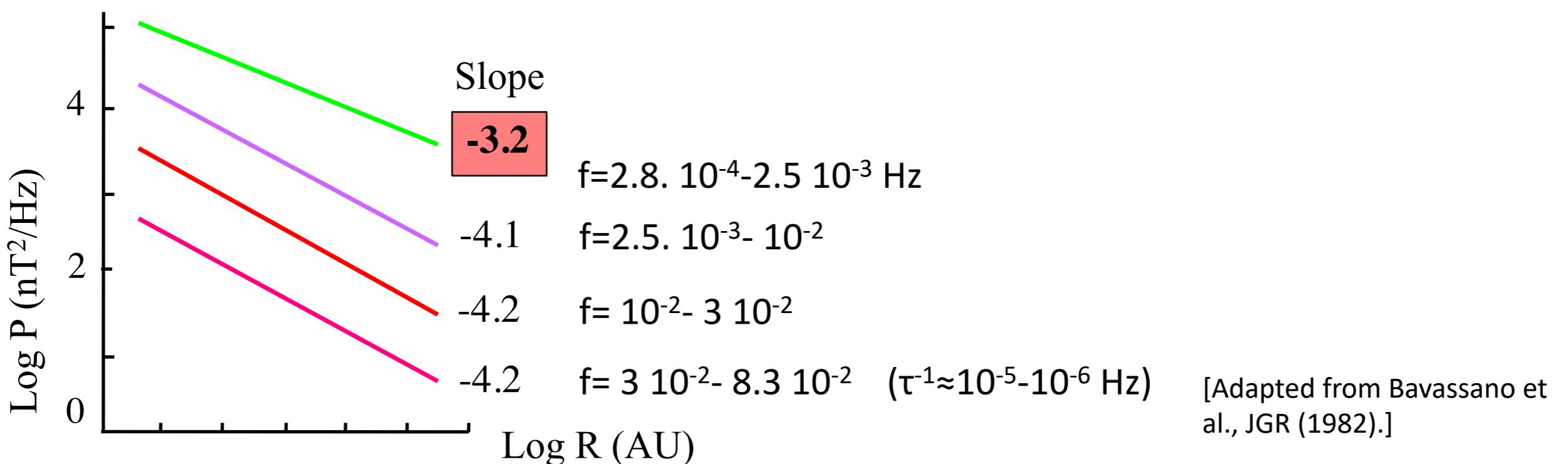
Radial evolution of fluctuations

Previous work using Helios during Alfvénic periods

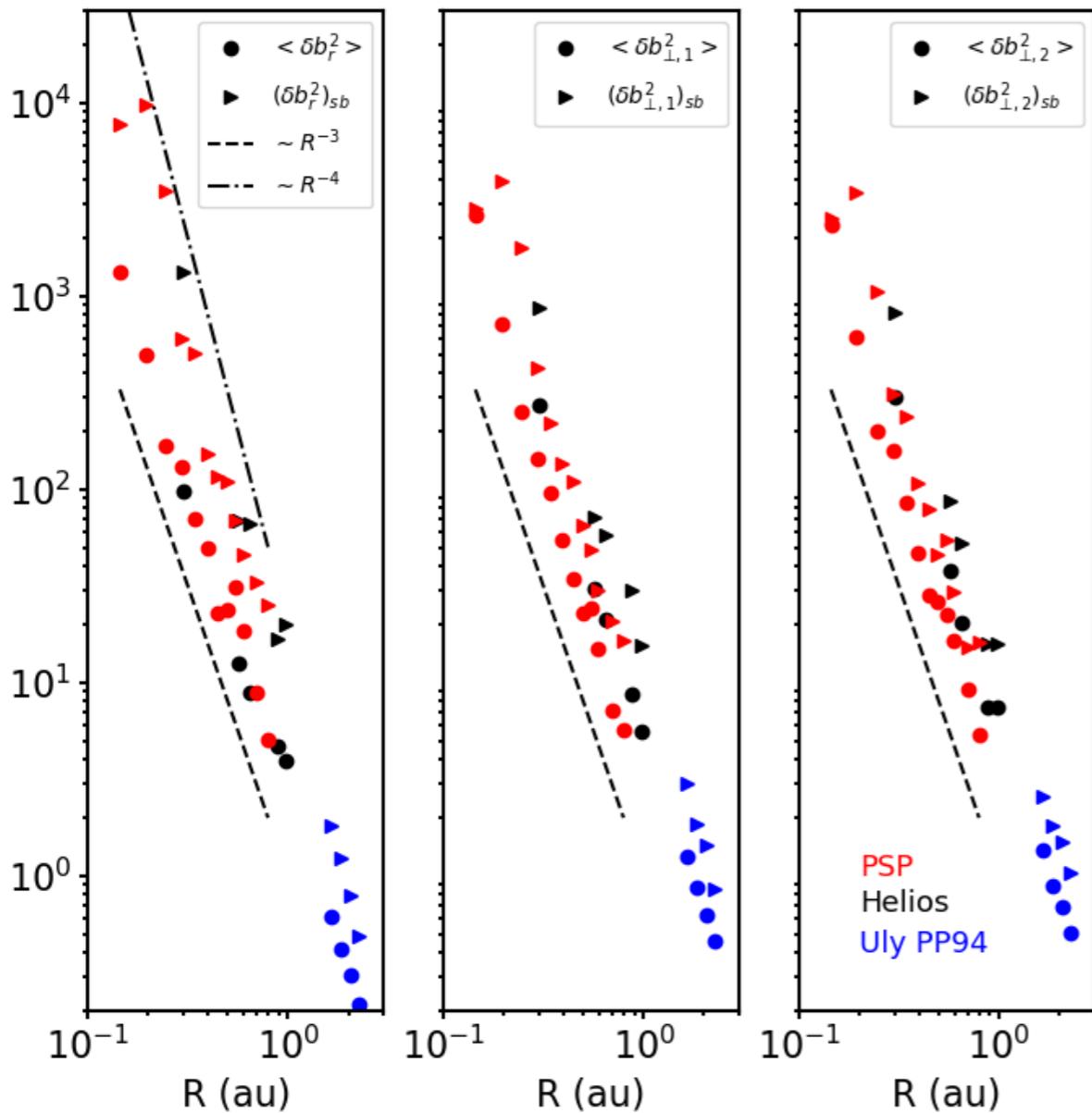
- In the WKB limit ($\omega\tau \gg 1$, $\tau = R/U$) the conservation law of wave action $S = E/\omega$ implies

$$|\mathbf{z}^-|^2 \propto \frac{V_a U}{(U + V_a)^2} \Rightarrow \delta b^2 \propto \frac{n V_a U}{(U + V_a)^2} \propto R^{-3}$$

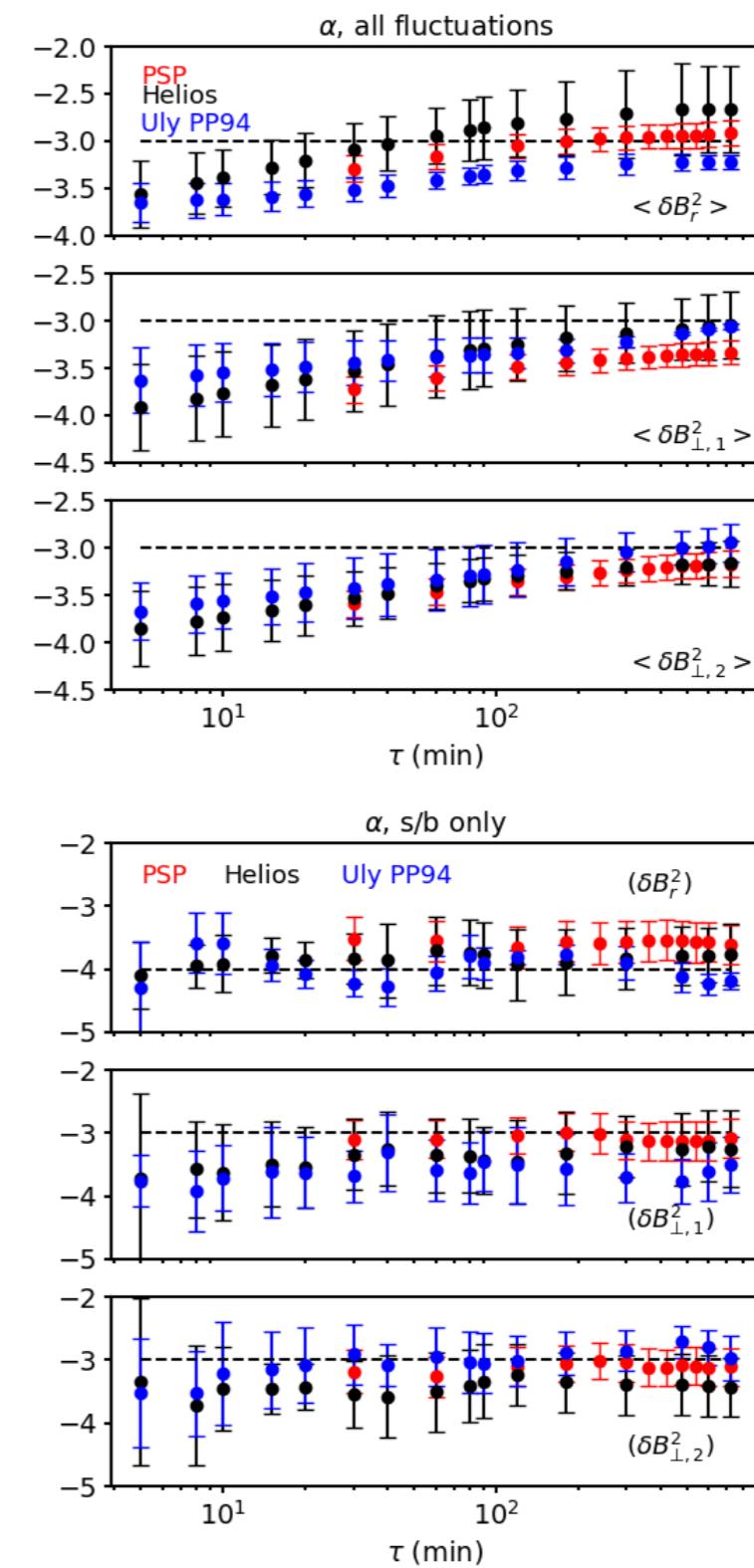
- Such scaling remains valid also for large amplitude fluctuations, provided nonlinearities are quenched, that is, for *locally* constant-B states (Hollweg 1974)



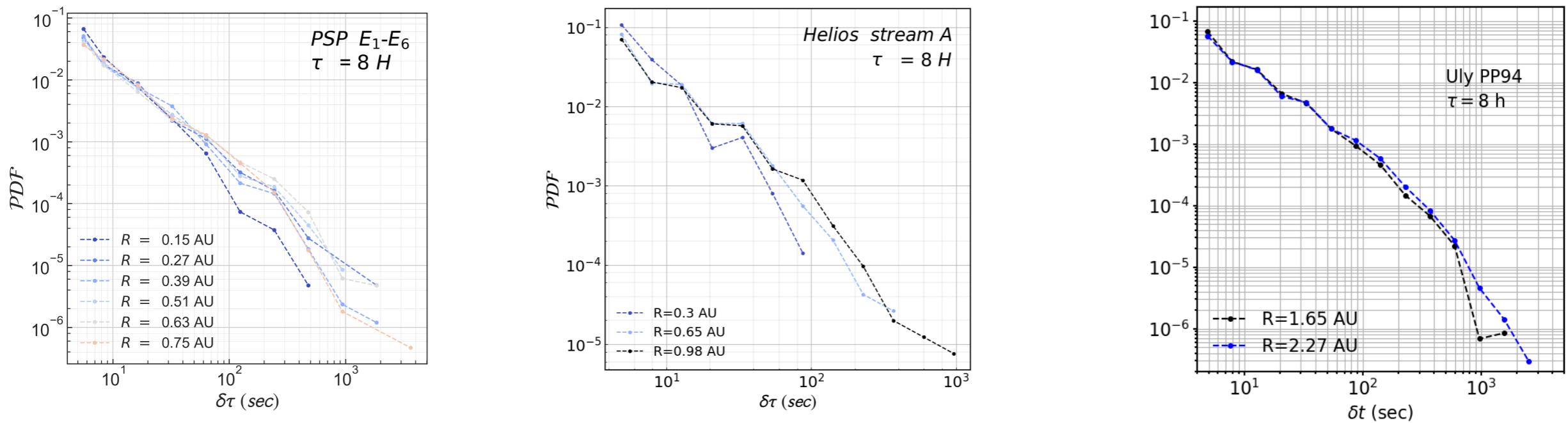
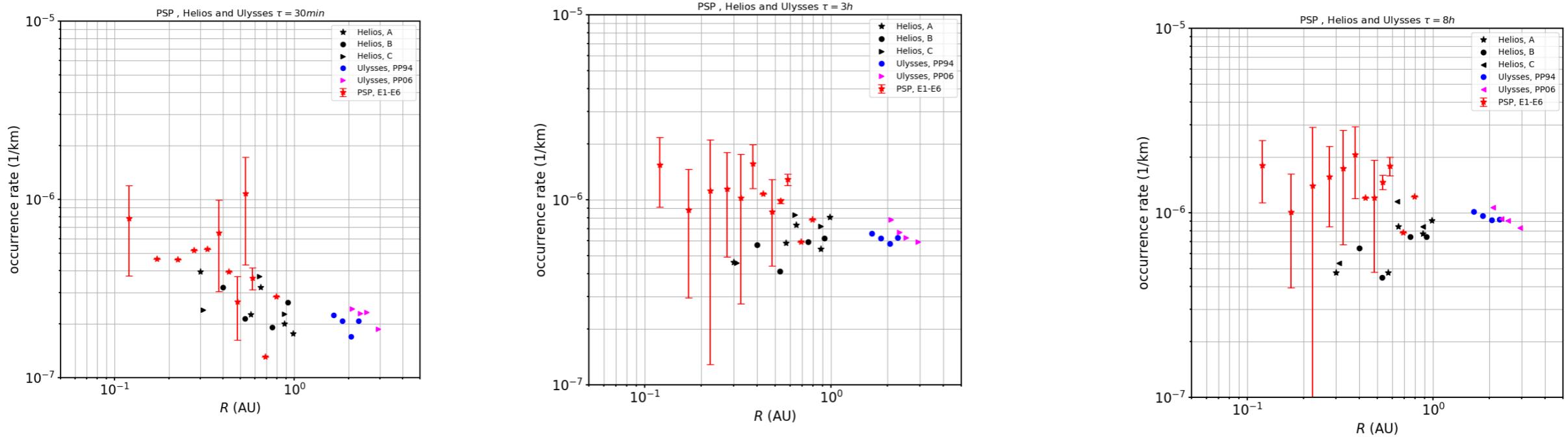
Radial evolution of fluctuations in the inner heliosphere from 0.1 to 3 AU



(Tenerani et al. in prep)



Switchbacks counts/km as a function of radial distance and pdf



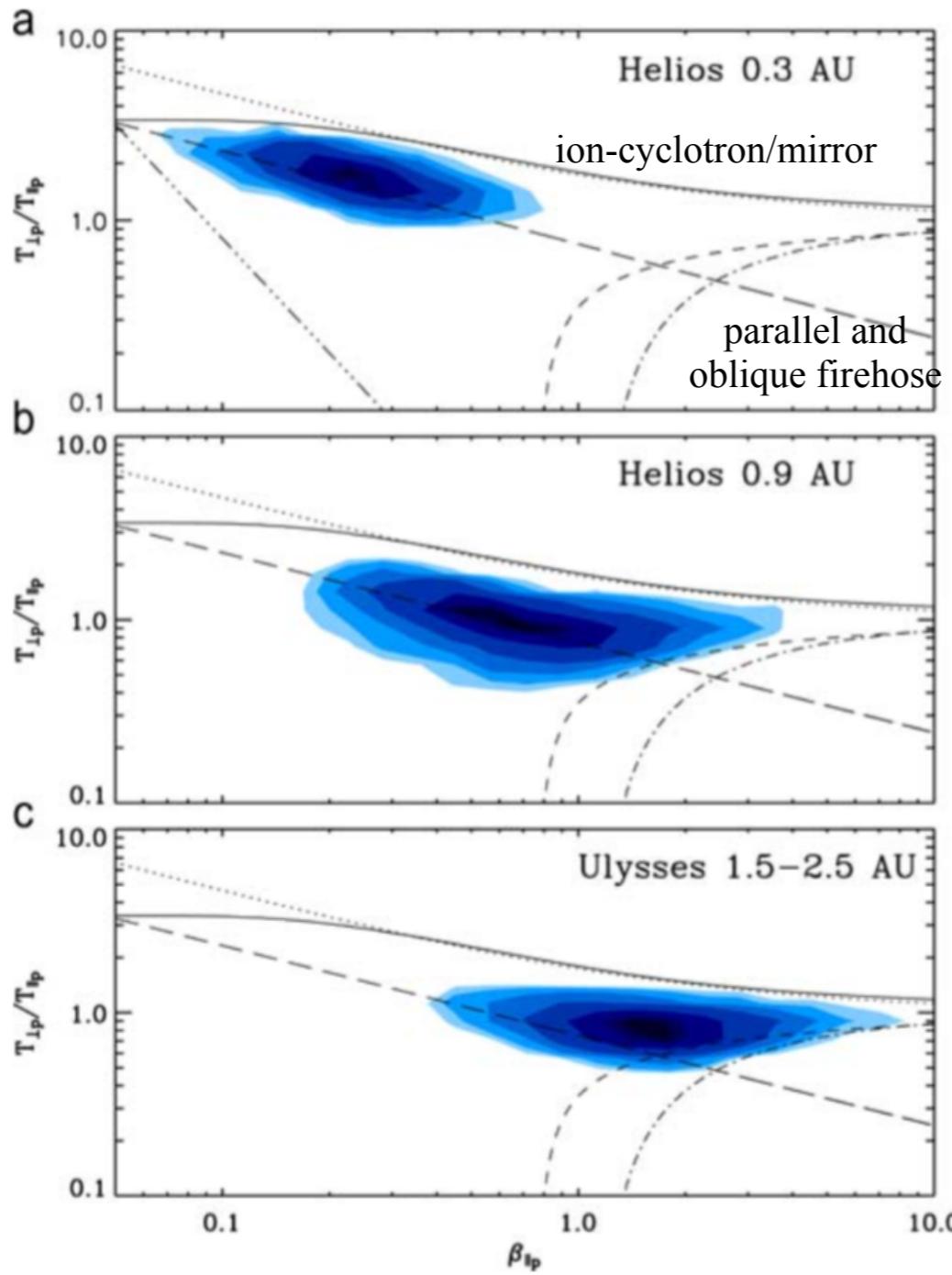
Where do switchbacks come from? How do they evolve?

- ★ Radial amplitudes of switchbacks decrease faster than the overall turbulent fluctuations. Specifically, their amplitude square scales approximately as $\delta B^2 \sim R^{-4}$ at all scales, a result that we interpret in terms of **saturated amplitudes**
- ★ The occurrence of switchbacks in the solar wind depends on the duration of the switchbacks and **both in-situ formation and decay are at play** in the solar wind
- ★ in-situ drivers like the expansion are more efficient in generating switchbacks at the larger scales, however, beyond 1 au we observe a net decrease of the cumulative counts per km of switchbacks, regardless of their duration
- ★ We conclude that it is possible that switchbacks of two or more type can coexist: those generated close to the sun and that decay as they propagate away, and those that are reformed or maintained alive in the inner heliosphere by a balance of expansion (or other in-situ drivers) and decay processes.
- ★ **How can such a peculiar nonlinear state can be achieved?** There has to be some process that comes into play that turns the field back to its highly Alfvénic state

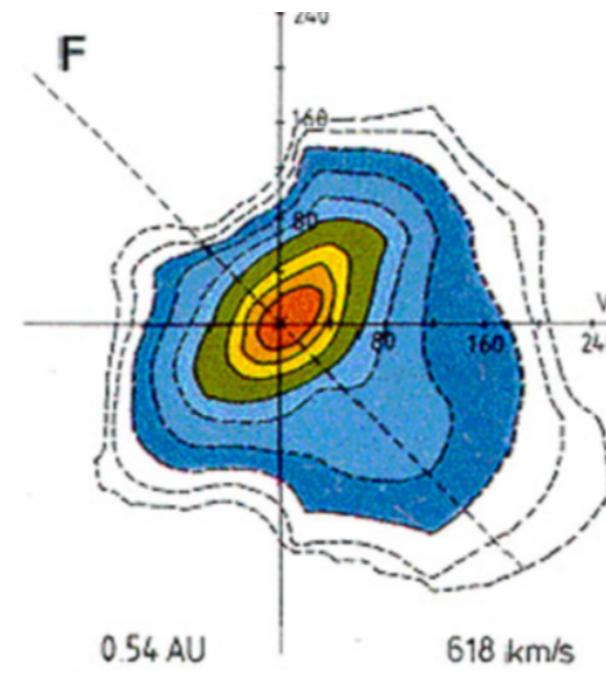
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Nonthermal features in the expanding solar wind



- Evolving temperature anisotropies
- Field-aligned beam at the local Alfvén speed
- Perpendicular heating (non-adiabatic expansion)



(Matteini et al. 2013)]

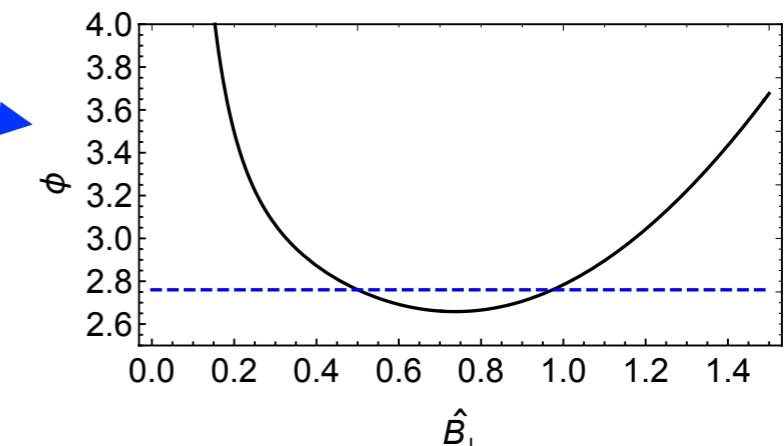
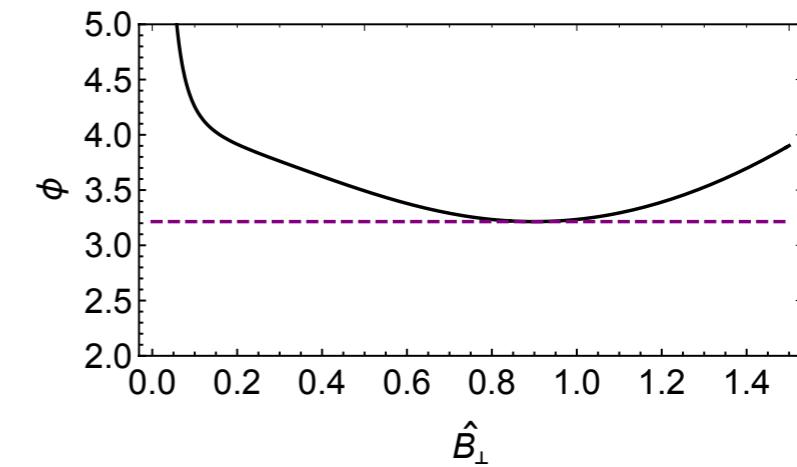
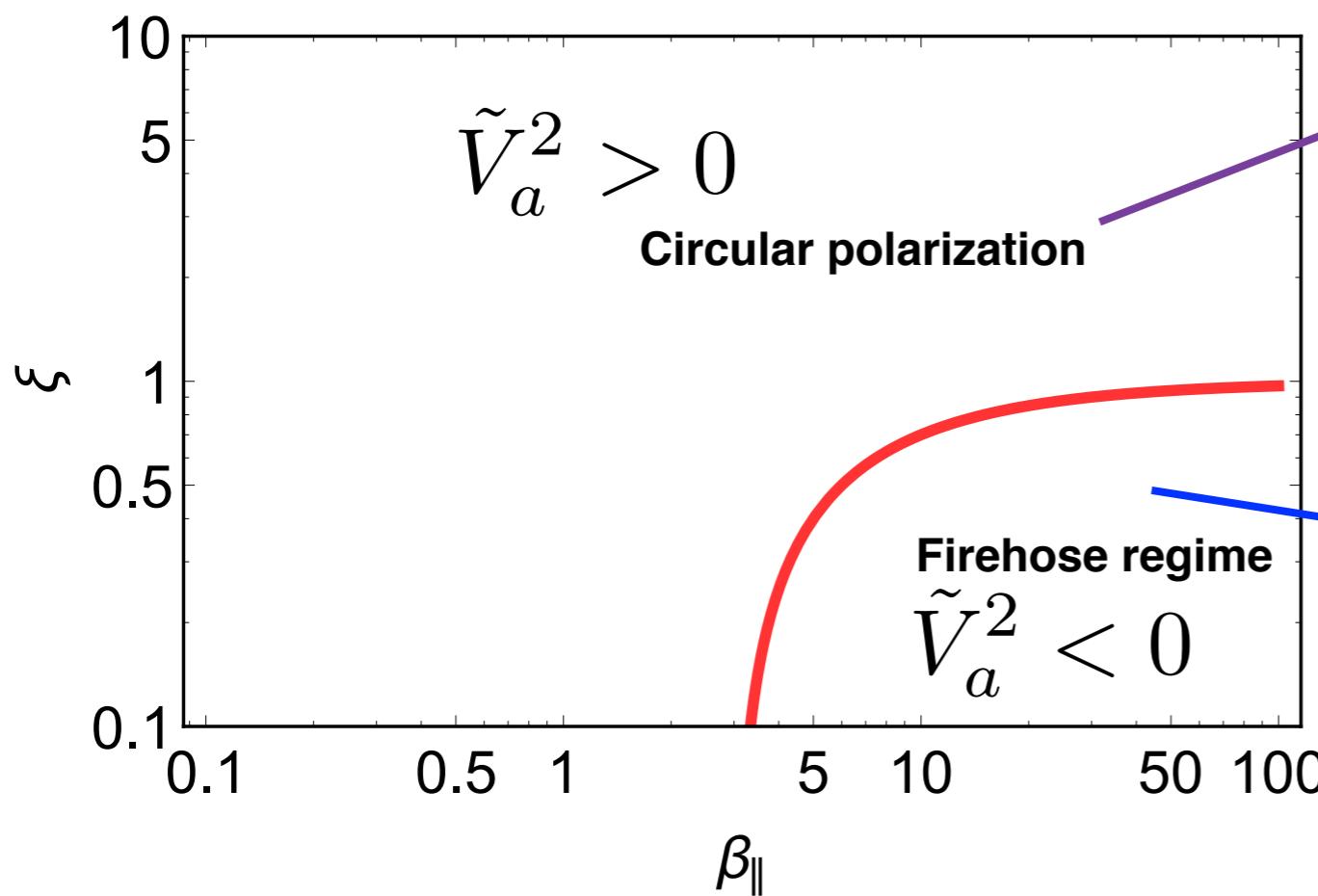
A new way to interpret constant-B states

$$\frac{\partial^2}{\partial t^2} \delta \hat{\mathbf{B}}_{\perp}(z, t) = \left(V_a^2 + \frac{1}{\rho_0} \frac{p_{\perp}(t) - p_{\parallel}(t)}{1 + \delta \hat{B}_{\perp}^2(t)} \right) \frac{\partial^2}{\partial z^2} \delta \hat{\mathbf{B}}_{\perp}(z, t). \\ = \tilde{V}_a^2$$

Energy conservation equation for a monochromatic wave:

$$\dot{B}_{\perp}^2 + \phi = E$$

$$\phi = V_a^2 k_0^2 + L^2 / B_{\perp}^2 + f(B_{\perp}^2, \xi \beta_{\parallel})$$



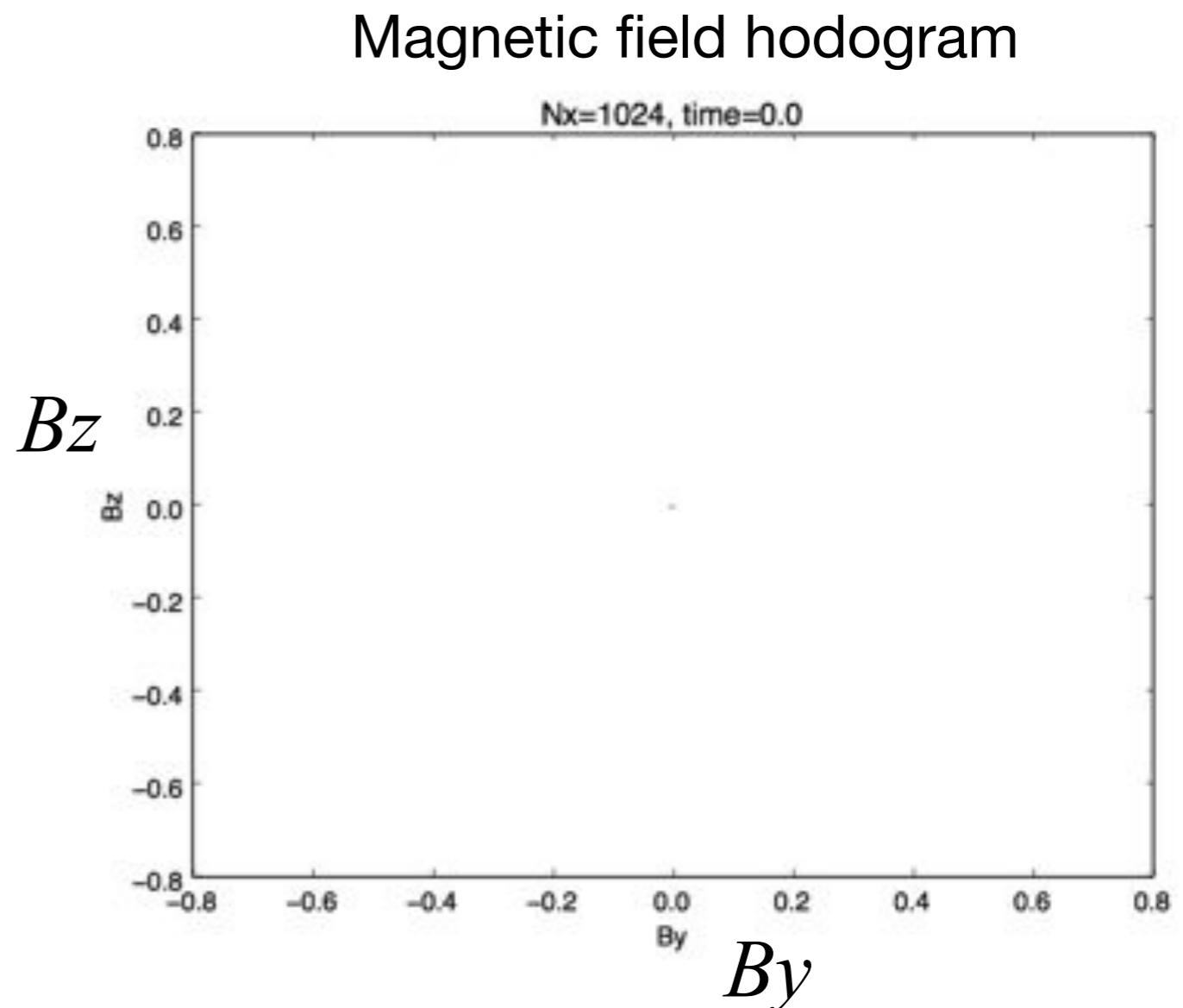
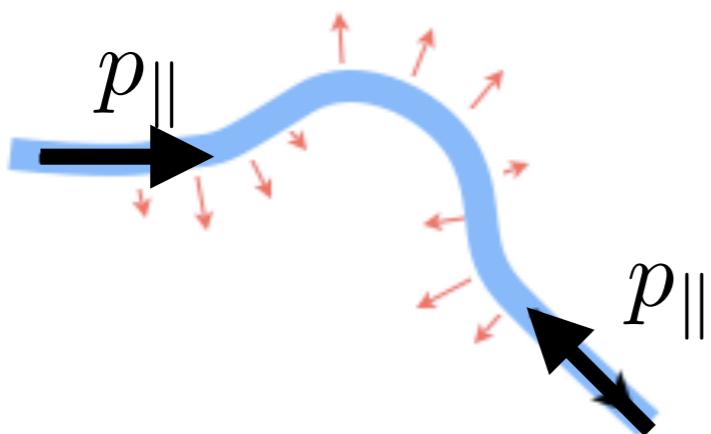
Revisiting the traditional firehose instability

- Linear instability of shear Alfvén waves in an anisotropy plasma*:

$$\omega = k \cos \theta V_a \sqrt{1 + \frac{\beta_{\parallel}}{2} \left(\frac{p_{\perp}}{p_{\parallel}} - 1 \right)}$$

- Purely growing modes when

$$\frac{\beta_{\parallel}}{2} \left(\frac{p_{\perp}}{p_{\parallel}} - 1 \right) < -1$$



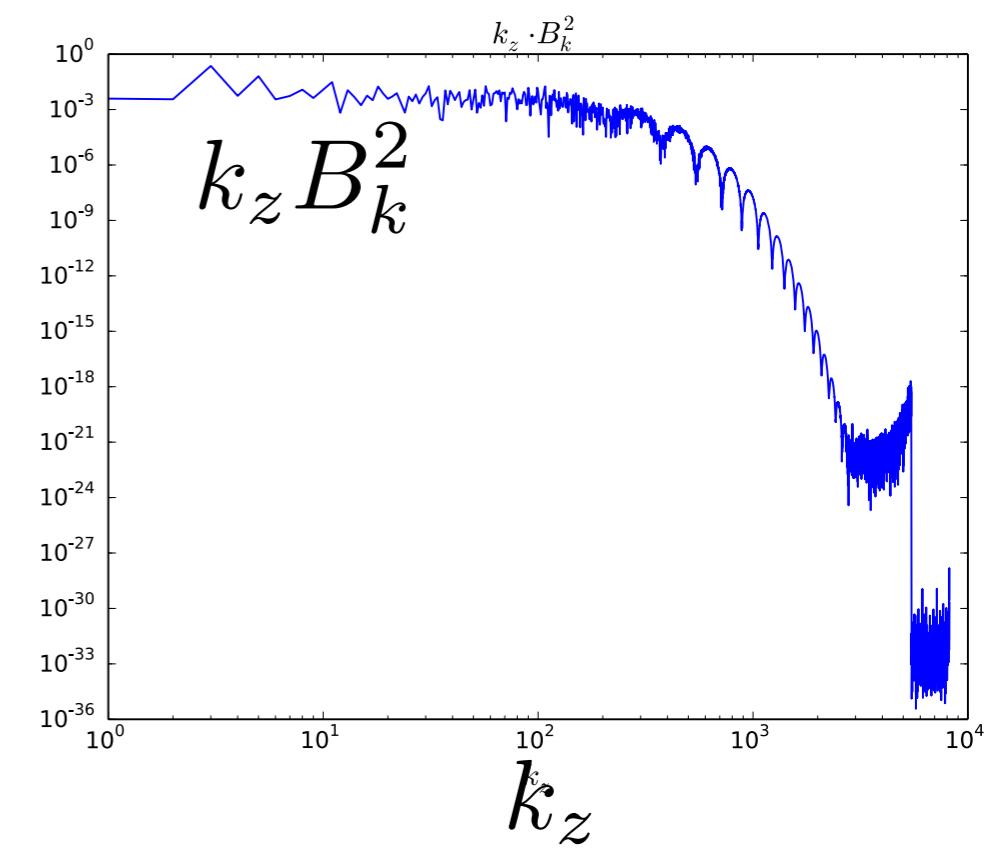
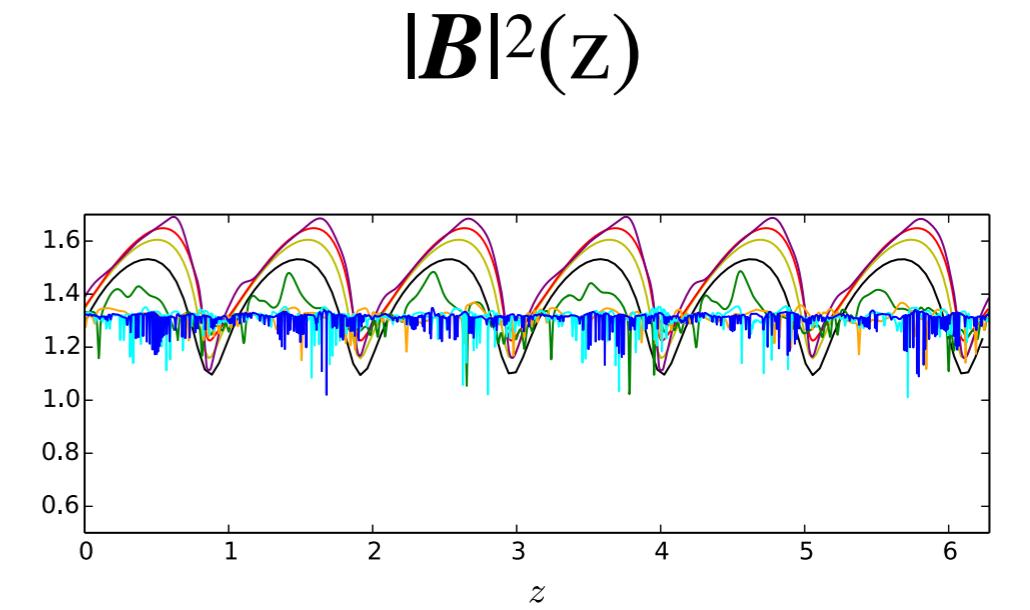
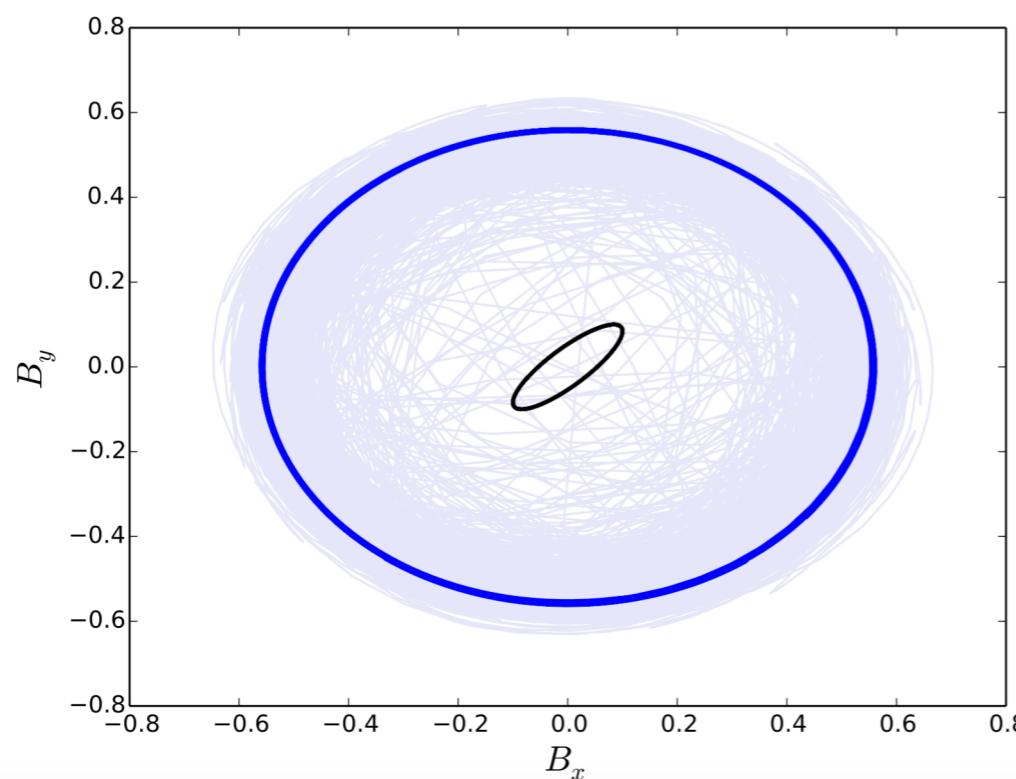
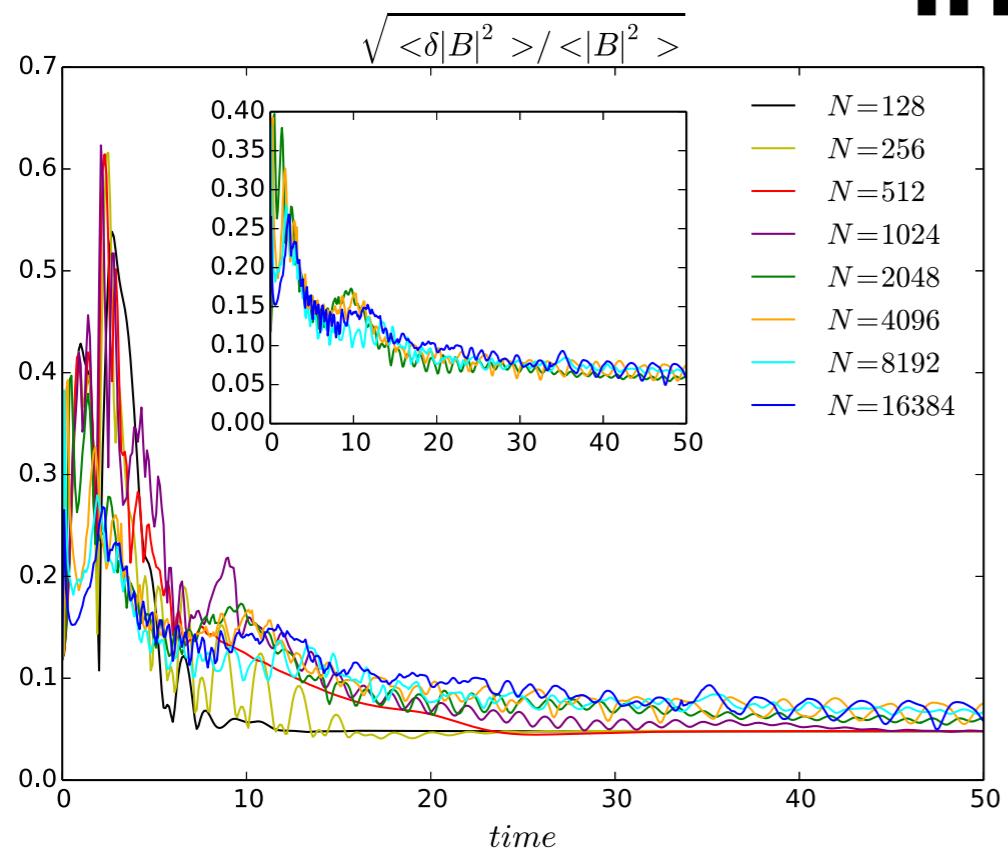
Nonlinear evolution of firehose instability from initial incoherent noise seeded in both transverse directions

*Rosenbluth 1956 LANL Report 3030

Parker 1958 PRL 109, 1874

Chandrasekhar et al. 1958 , Proc. Roy. Soc.

Numerical results of firehose instability



Theoretical interpretation

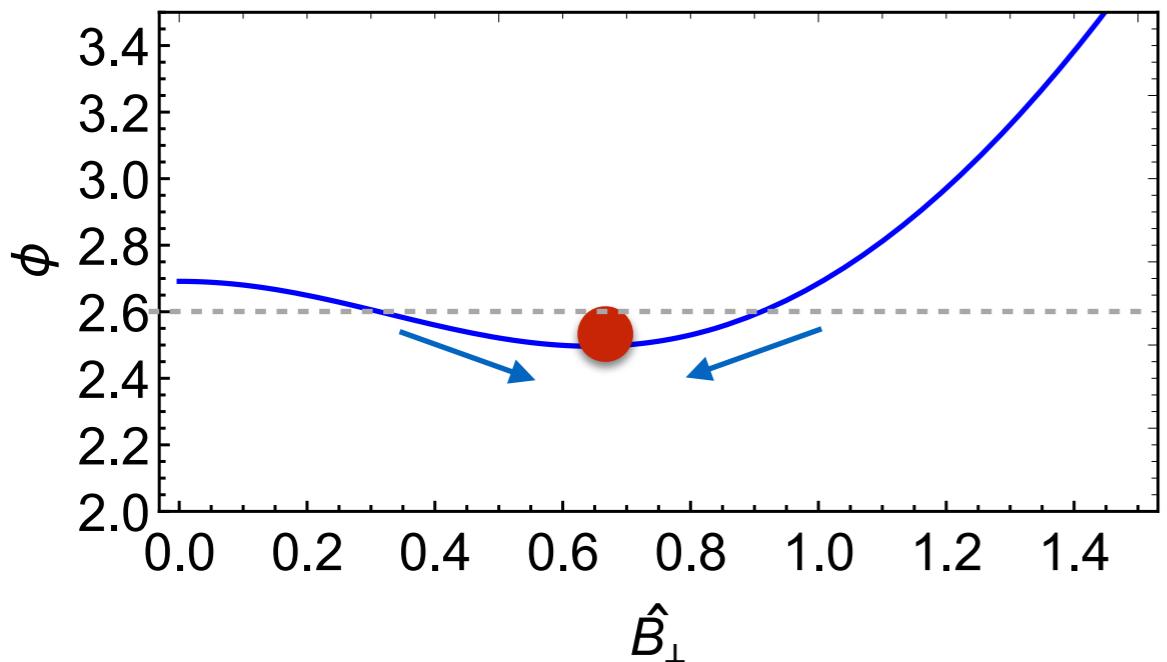
$$\frac{\partial^2}{\partial t^2} \delta \mathbf{B}_\perp(z, t) = \cos \theta_0 \frac{\partial^2}{\partial z^2} \left(\tilde{V}_a^2(z, t) \delta \mathbf{B}_\perp(z, t) \right)$$

decomposition in 2 terms: **mean field** term (i.e. $\langle B^2 \rangle$) + **fluctuations of B^2**

$$\ddot{B}_{k,i}(t) = -\frac{d\phi_k}{dB_{k,i}} + Ck^2 \sum_{p \neq k, q} B_{p,i} (\mathbf{B}_{p-k-q} \cdot \mathbf{B}_q)$$

coupled oscillators

nonlinearity

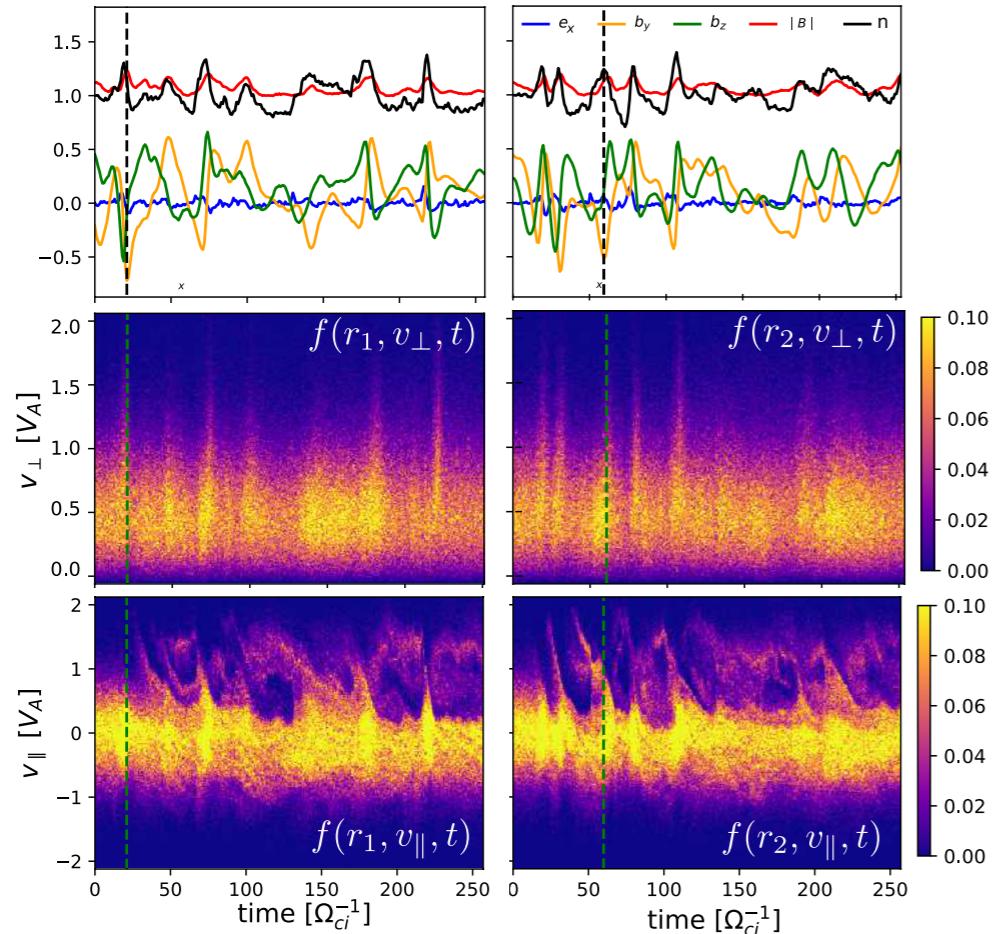


saturation condition

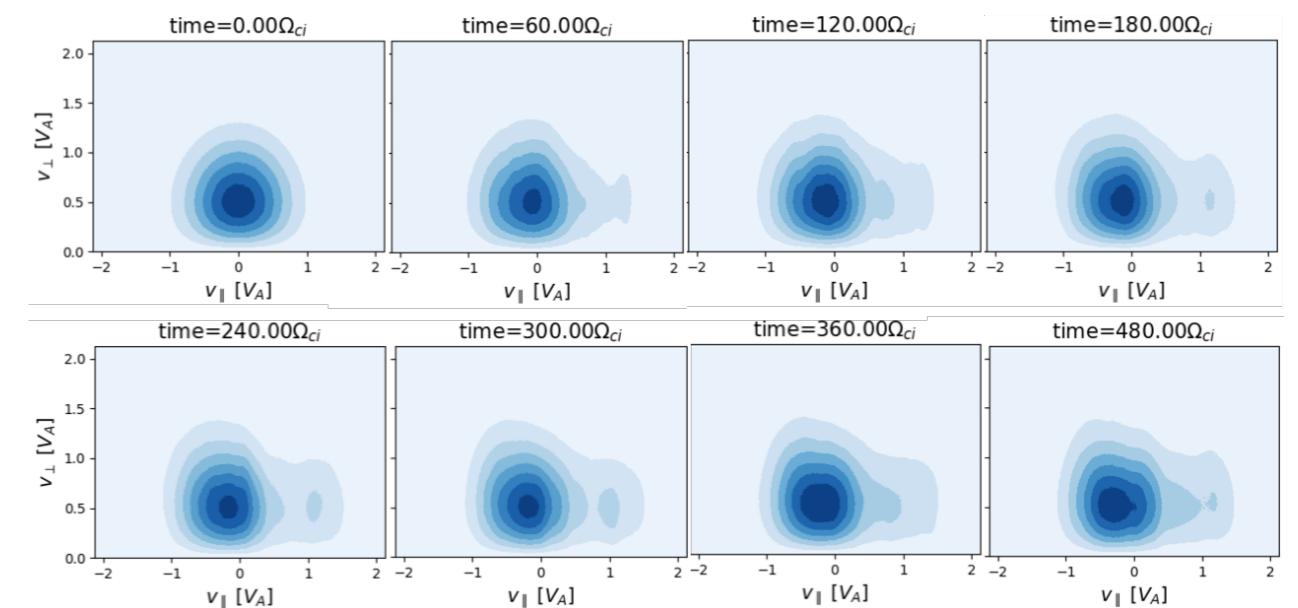
$$1 + \frac{\beta_{||}}{2} \frac{1}{\langle B^2 \rangle} \left(\xi \sqrt{\frac{\langle B^2 \rangle}{\langle B^2(0) \rangle}} - \frac{\langle B^2(0) \rangle}{\langle B^2 \rangle} \right) = 0$$

(Tenerani & Velli ApJL 2018)

Alfvén wave steepening & collapse



- An initial Alfvénic fluctuation steepens due to a combination of dispersion and nonlinearities
- At the steepened front a field aligned electric field forms that accelerates the particles (protons) to form a beam
- As a result, the field-aligned electric field and compressible fluctuations are damped nonlinearly



Top: fields and distribution function contour as a function of time in one point in space

Right: evolution of the averaged distribution function

Summary and conclusion

- ▶ We observe 2 populations of Alfvénic fluctuations.
 - ▶ A population roughly following the predicted WKB at the larger scales
 - ▶ The switchbacks corresponding to ‘saturated’ fluctuations
- ▶ Switchbacks both decay and reform
- ▶ Expansion can drive switchbacks in the inner heliosphere, but other types of switchbacks cannot be ruled out
- ▶ Open question: what is the physical mechanism that enforces the constant-B constraint (i.e. incompressibility) on expanding fluctuations!?
 - ▶ Parametric decay and wave collapse may prevent uncontrolled growth of fluctuations at several tens of solar radii, and may also cause s/b decay. But where are compressible effects?
 - ▶ Kinetic simulations of large amplitude fluctuations provide a possible route to the understanding of the evolution of Alfvénic fluctuations towards an incompressible nonlinear state